Spectroscopy of Proton-Odd Transfermium Nuclei

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Spectroscopy of the proton-odd transfermium isotopes ^{247}Es, ^{251}Md and ^{255}Lr has been performed using decay and in-beam techniques. Single particle states have been studied at GANIL and the University of Jyväskylä using spectroscopy after α decay of ^{255}Lr. Prompt gamma-ray spectroscopy of ^{251}Md and ^{255}Lr was performed at Jyväskylä using the Jurogam array coupled to the RITU separator. These experimental results are compared to new Hartree-Fock-Bogoliubov calculations.

Future prospects for the study of the heaviest elements at GANIL with the existing facility and the future SPIRAL2 and LINAG beams are presented.

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1. Introduction

Mendelevium (Z=101) and Lawrencium (Z=103) isotopes have been discovered nearly 50 years ago at Berkeley and Dubna. However, very scarce information on their structure has been obtained up to now. For instance, the ground-state spin and parity of most Md and Lr isotopes remains uncertain. The nuclear structure of transfermium isotopes and the identification of single-particle states is of great importance to understand the stability of the heaviest elements, which is entirely due to shell effects. Proton orbitals that are thought to be responsible for the spherical super-heavy shell closure are found at the Fermi surface of the deformed nuclei around Z=102. Detailed spectroscopy of the transfermium nuclei is therefore essential to move toward a better understanding of the limits of stability. In-beam gamma spectroscopy has become possible in this mass region over the past ten years

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with the coupling of efficient recoil separators and arrays of germanium detectors at the target position. The pioneering prompt γ-ray spectroscopy of ^{254}No performed in parallel works at Argonne [1] and at the University of Jyväskylä (JYFL) [2] has triggered experimental and theoretical works in the transfermium region (for a review of recent works, see *e.g.* [3, 4]; see also [5] in these proceedings). Rotational bands in the neighbouring even-even ^{252}No and ^{250}Fm have been observed. Recently, isomeric states have been studied in ^{254}No, giving insight into the single-particle structure through particle-hole excitations [6, 7]. Odd nuclei are crucial since they also provide information on the single-particle structure. Figure 1 shows the single-particle spectrum obtained from an Hartree-Fock-Bogoliubov calculation [8]. Information on the next magic proton number can come from the location of the [521]$1/2^-$ orbital, which originates from the $2f_{5/2}$ shell above the predicted shell gap at Z=114. This orbital becomes active in the Z $\sim$ 102 region where the quadrupole deformation β_2 is found to be ~ 0.3. Only a few odd isotopes have been studied so far using prompt gamma-ray spectroscopy: the neutron-odd ^{253}No [9] and the proton-odd ^{251}Md and ^{255}Lr that will be presented in section 3.

Complementary to prompt spectroscopy, combined gamma and conversion electron spectroscopy after α decay provides details of the single-particle structure. Alpha-decay is indeed very sensitive to the details of the initial and final wave functions. Alpha-electron and α-gamma coincidences provide additional information on the spin and parity of the populated states. This technique has been applied in the spectroscopy of ^{255}Lr, ^{251}Md and ^{247}Es and will be presented section 2.

2. Spectroscopy after α decay of ^{255}Lr

Two experiments aimed at the study of the ^{255}Lr decay have been performed at JYFL and at GANIL (E375 experiment). In both experiments, the ^{255}Lr nuclei were populated using the fusion-evaporation reaction ^{209}Bi(^{48}Ca,2n)^{255}Lr. At GANIL and JYFL, fusion-evaporation products were separated from the beam and the large background of parasitic reactions such as fission, transfer and elastic scattering by the LISE Wien filter and RITU separator, respectively. The detection setup at the focal plane consisted in both cases of a time-of-flight detector, a Double Sided Silicon Striped Detector for implanted recoils and α particles, a tunnel of silicon detectors for electron spectroscopy, and Ge detectors for gamma-ray spectroscopy. Details of the experimental devices can be found in [8].

The level schemes resulting from the considerations presented in this section are shown in figure 2.

New alpha lines from the ^{255}Lr and ^{251}Md decays were observed. The al-

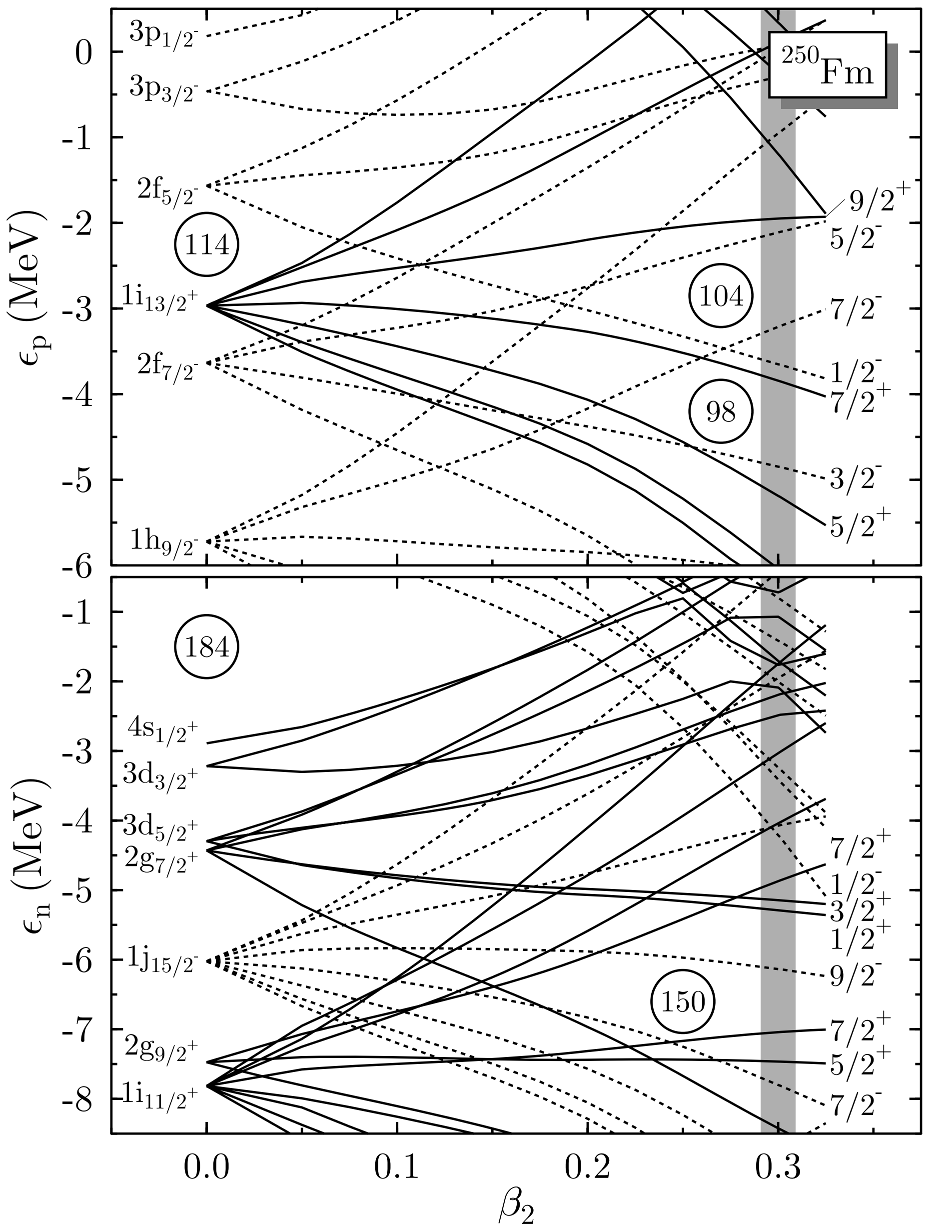

Fig. 1. Single-particle spectra of ^{250}Fm for protons (top) and neutrons (bottom) obtained with the SLy4 interaction. The vertical grey bar indicates the range of ground-state deformations predicted for this and neighbouring nuclei [8].

pha decay of ^{251}Md is found to be in coincidence with two gamma-rays of 293 keV and 243 keV, while no coincidences with electrons could be observed. This allows us to deduce the multipolarity of the transitions and hence the spin and parity of ^{251}Md ground-state to be $7/2^-$. The 50 keV transition from $9/2^+$ to $7/2^+$ in ^{247}Es is deduced to have M1 character. This almost fully converted transition is emitted in coincidence with the 7550 keV alpha transition, resulting in a partial summing in the silicon detector and hence in a peak at 7590 keV. GEANT 4 [10] simulations including atomic processes were performed and reproduce within 4 keV the experimental data. Fluorescence, Coster-Kronig and Auger electron emission yields taken from [11] were used. The observed summing effect is therefore the indirect probe of atomic effects which could so far not be studied in this mass region. The large uncertainties in these atomic yields (for instance the uncertainty in the L1 fluorescence yield of 20 %) may account for the small discrepancies between our simulations and experimental data. New atomic calculations are in progress and preliminary results [12] indicate that the L1 fluorescence yield taken from [11] is overestimated by about 10%. More detailed calculations are in progress. It is important to note that a $3/2^-$ state is expected at low excitation energy in ^{247}Es. Since selection rules do not favour the feeding of this state, it could not be observed. The ground-state spin and parity of ^{247}Es remains therefore uncertain.

In ^{255}Lr, an isomeric state having an half-life of 2.5 s has been observed. Using the intensities and half-lives of four alpha-lines allows us to deduce a $1/2^-$ ground-state and $7/2^-$ isomeric state for ^{255}Lr.

The experimental data have been compared to new Hartree-Fock-Bogoliubov calculations using the Skyrme interaction SLy4. The same formalism as in [13] is used. Theoretical calculations were performed for ^{247}Es, ^{251}Md and ^{255}Lr, but also for large isotopic chains. It is indeed instructive to make comparisons with all available experimental data, and to observe the evolution of single-particle states as a function of the neutron number.

The experimental data clearly indicate a deformed shell closure at N=152. As an example, the distance between the up-sloping $7/2^-$ and down-sloping $7/2^+$ reaches a maximum at N=152 [8, 14]. HFB calculations favour however N=150 as a magic deformed number as shown in figure 1, though the distance between the two corresponding spherical shells seems correct. Experimentally, the $1/2^-$ and $7/2^-$ states are always observed close in energy, which suggests that the spherical $2f_{5/2}$ should be slightly pushed up. The position of the $3/2^-$ state (suspected at low excitation energy in $^{243-249}$Es isotopes) would be better reproduced if the spherical $2f_{7/2}$ shell shell was also located slightly higher. This could be understand as a consequence of a known overestimation of the spin-orbit splitting by HFB calculations using the SLy4 interaction [15]. Combining all these considerations results in a

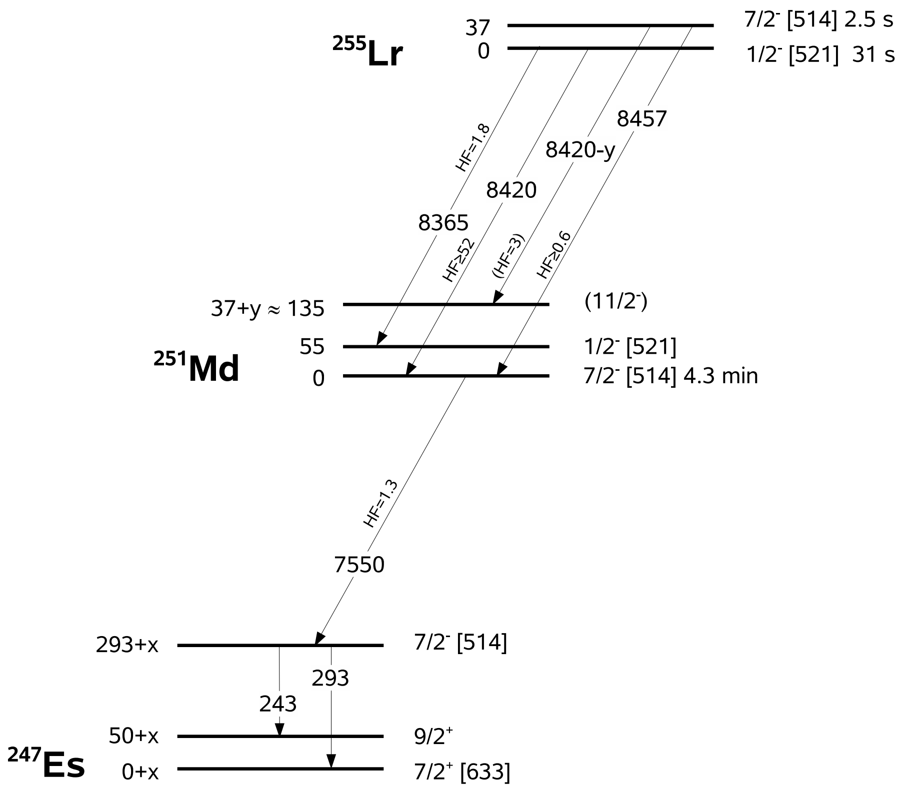

Fig. 2. Level scheme of ^{247}Es, ^{251}Md and ^{255}Lr deduced from the two experiments performed at GANIL and JYFL [8].

slight underestimation of the Z=114 spherical gap, which remains however too small to establish a major spherical shell closure.

3. Prompt gamma-ray spectroscopy of ^{255}Lr and ^{251}Md

The prompt gamma-ray spectroscopy of ^{251}Md and ^{255}Lr was performed at JYFL using the RITU separator and the Jurogam germanium array. Details of the experimental technique can be found in *e.g.* [16]. The excitation function for the fusion-evaporation reaction ^{205}Tl(^{48}Ca,2n)^{251}Md was measured for the first time and shows a maximum of $\sim$ 760 nb at at center-of-target energy of 214 $\pm$ 2 MeV [17]. ^{255}Lr was populated using the fusion-evaporation reaction ^{209}Bi(^{48}Ca,2n)^{255}Lr.

The ^{251}Md spectrum was obtained using the Recoil Tagging (RT) technique. Indeed, the small ~ 10 % α-branching ratio does not allow the Recoil Decay Tagging (RDT) technique to be used and the excitation-function measurement shows that the contribution from other channels is negligible. The spectrum shows complicated structures (see figure 3) which could be identified using gamma-gamma coincidences. A rotational band consisting of 8 transitions could be unambiguously observed. This sequence is observed without a signature partner, which is usually a hint for a K=1/2 configuration. As shown in the previous section, the [521]1/2 orbital from the $2f_{5/2}$ spherical shell is the only possible candidate. We have calculated within the HFB formalism the moment of inertia of rotational bands built on the low-lying single-particle states. The similarity of the results for the different configurations does not allow us to draw any conclusions.

We have therefore calculated the electromagnetic properties of rotational bands. From the calculated wave functions, it is possible to deduce the reduced B(E2) intra-band and B(M1) inter-band transition probabilities. Details of the formalism can be found in [19, 20]. Using the calculated transition energies and the electron conversion coefficients, we have calculated the transition ratio T(M1)/T(E2) which can be compared to experimental data. Our calculations show that the structure built on the $[514]7/2^-$ band-head should decay mainly via two E2 cascades with almost equal intensity, while the structure built on the $[633]7/2^+$ band-head should be dominated by M1 inter-band transitions. In the special case of the [521]1/2 orbital, the $\alpha = -1/2$ signature partner is shifted up compared to the favored $\alpha = +1/2$ signature band, the signature splitting being the dominant contribution in the deduced T(M1)/T(E2) ratio. Our calculations shows that the [521]1/2 configuration has a decoupling parameter $a \sim 1$, and only the decay pattern for the band built on this configuration is compatible with the experimental data.

Since the cross section for the fusion evaporation reaction ^{209}Bi(^{48}Ca,2n)^{255}Lr is only about 300 nb, gamma-gamma coincidences could not be used for an unambiguous identification of rotational structures. However, the spectrum shown in figure 3 suggest the presence of two rotational structures, one without and the other with a signature partner. The α-branching ratio of ^{255}Lr is large enough for using the RDT technique. The presence of the $7/2^-$ 2.5 s isomer (see previous section) allows us to select gamma-rays feeding this state. The spectrum gated on the $7/2^-$ isomer decay is compatible with two signature partner bands, in agreement with the decay pattern calculated for ^{251}Md (similar electromagnetic properties are expected for both isotopes). The spectrum gated on the $1/2^-$ ground-state decay displays peaks compatible with the $1/2^-$ and $7/2^-$ rotational bands. Indeed, part of the isomeric decay proceeds via the ground state.

Results obtained in ^{251}Md, ^{255}Lr experiments are therefore consistent

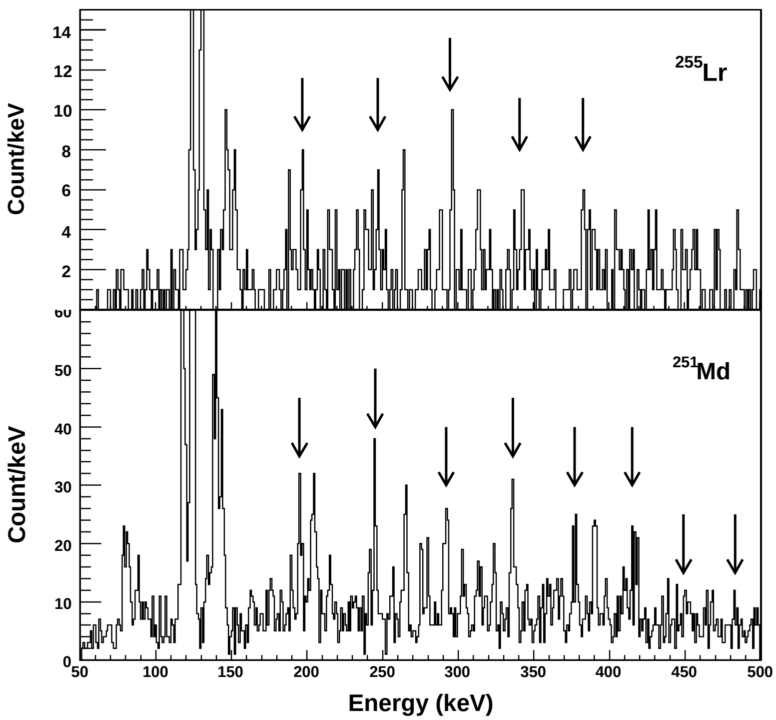

Fig. 3. Comparison between the prompt gamma-ray spectra of ^{255}Lr [18] (top) and ^{251}Md [17, 19] (bottom).

with the observation of $1/2^-$ and $7/2^-$ states with rotational bands built on top of these quasi-particle states.

The comparison of the gamma-ray spectra displayed in figure 3 shows striking similarities. Indeed, the bands interpreted as built on the [521]1/2 orbital in ^{251}Md and ^{255}Lr have similar energies within 2-3 keV. It remains to be understood whether these similarities are accidental, or whether there are similarities with the identical band phenomenon observed in many superdeformed bands [21].

4. Heavy-element studies at GANIL

The LISE spectrometer in its FULIS configuration has been used to perform gamma and electron spectroscopy after α decay of ^{255}Lr: see section 2. This facility has also been used for the search of superheavy elements [22]. The heavy-element program at FULIS will continue with the formation studies of super-heavy nuclei with nearly symmetric reactions [23]. Recent theoretical work suggest that the fusion-evaporation cross section is reduced for nearly symmetric systems leading to Z=104-106. However, the reduction gets smaller for heavier Z, especially if more neutron-rich systems are formed and partners with closed shells are used. The predictions differ by large factors and need to be clarified experimentally.

Since 2004, we have investigated the possibility of performing prompt spectroscopy of heavy elements with the EXOGAM germanium array and the VAMOS spectrometer. The performances of these two devices are well adapted to the spectroscopy of transfermium elements. EXOGAM is well adapted to the detection of low multiplicity cascades with an efficiency of about 25% in the energy range of interest. For a cascade of 6 emitted gamma-rays, the probability to detect at least one gamma-ray is about 80%. The VAMOS spectrometer is also well adapted to the study of very asymmetric reactions. The recoil angle and velocity dispersion for such reaction is large and the transmission of other existing spectrometers or separators coupled to a germanium array are usually below 10 %. VAMOS has a large angular acceptance and the transmission is expected to be larger than 50 %. A crucial point in these experiments is the suppression of the primary beam. A first test was performed using the reaction ^{208}Pb(^{18}O,4n)^{222}Th using the VAMOS Wien filter. Excellent performances were obtained and the feasibility of the RT technique was demonstrated. The dispersive mode of VAMOS should be tested for very asymmetric reactions using *e.g.* a ^{22}Ne beam on ^{197}Au, ^{208}Pb and ^{238}U targets. A good separation of the fusion-evaporation residues from the primary beam is expected since their magnetic rigidities differs by a factor $\simeq 3$.

Using the RT technique requires an highly segmented focal plane setup. Such a Si wall called MUSETT is being developed and will be installed at the focal plane of VAMOS in 2008. Since recoil energies are very low for very asymmetric reactions, window-less detectors will be used. The 1024 strips of the Si wall will be equipped with ASICs electronics.

A limitation of EXOGAM arises from its counting-rate capability due to the analogue electronics. It it foreseen to upgrade the array, called EXOGAM 2, with digital electronics. It has been proved that a counting rate of $\sim$100 kHz can be used without major deterioration of the energy resolution. Pulse shape analysis of the signals will also be performed to determine the position of the first interaction of the gamma-rays for a better Doppler correction.

4.1. Prospects with the radioactive and high-intensity stable beams from SPIRAL 2

The SPIRAL 2 facility will deliver neutron-rich fission fragments and high-intensity stable beams from the LINAG driver. Stable beam intensities of more than 10^{14} particles per second (pps) will allow detailed spectroscopy after alpha decay of transactinide elements. This corresponds, as an example, to the detection of about 1000 atoms of elements 114 per week. Dealing with such high beam intensities requires a new separator with high performances. The project S^3 aims at building for the first LINAG beams in 2011 a separator followed by a spectrometer with its associated focal plane detection system.

Neutron-rich fission fragments will be delivered by SPIRAL 2 with intensities up to 10^{11} pps. Symmetric reactions using beams in the Kr or Xe region are promising although detailed reaction mechanism studies have to be performed. Besides decay spectroscopy studies, we foresee to perform prompt gamma-ray spectroscopy studies using the VAMOS spectrometer. The AGATA gamma tracking array will be available during campaigns at GANIL and will provide unprecedented efficiency. The preliminary phase of AGATA, the "demonstrator" should be installed at GANIL in 2009 and coupled to the VAMOS and EXOGAM arrays.

Details of the physics program with SPIRAL 2 can be found in [24].

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